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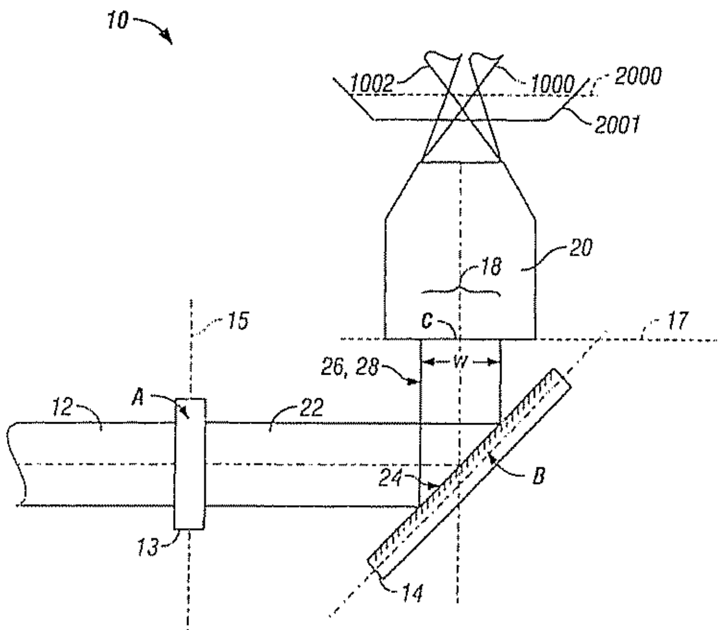
(54) Title: APPARATUS AND METHOD TO GENERATE AND CONTROL OPTICAL TRAPS TO MANIPULATE SMALL PARTICLES



(57) Abstract: The present invention relates generally to an apparatus and method to generate and control optical traps (1000, 1002) for manipulation of small particles. An upstream modification of an input laser beam (12, 22) provides a beam with a square or other preselected. cross section of intensity which can be used to form optical traps (1000, 1002) with a corresponding cross section of intensity.

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APPARATUS AND METHOD TO GENERATE AND CONTROL OPTICAL TRAPS TO MANIPULATE SMALL PARTICLES.

BACKGROUND OF THE INVENTION

Throughout this application various publications are referenced. The disclosures of these publications in their entireties are hereby incorporated by reference in this application in order to more fully describe the state of the art to which this invention pertains.

1. Field of the Invention

The present invention relates generally to optical traps. In particular, the invention relates to an apparatus, system and method for applying optical gradient forces to form a plurality of optical traps to manipulate small particles.

2. Discussion of the Related Arts

An optical tweezer is an optical tool which utilizes the gradient forces of a focused beam of light to manipulate particles with dielectric constants higher than the surrounding media. To minimize its energy such particles will move to the area where the electric field is the highest. Stated in terms of momentum, the focused beam of light produces radiation pressure, creating small forces by absorption, reflection, diffraction or refraction of the light by a particle. The forces generated by radiation pressure are almost negligible--a light source, such as a diode-pumped Nd:YAG laser operating at 10mW, will only produce a few picoNewtons. However, a few picoNewtons of force is sufficient to manipulate small particles.

Other optical tools which can be used to manipulate small particles include, but are not limited to, optical vortices, optical bottles, optical rotators and light cages. An optical vortex, although similar in use to an optical tweezer, operates on an different principle.

An optical vortex produces a gradient surrounding an area of zero electric field which is useful to manipulate particles with dielectric constants lower than the surrounding media or which are reflective, or other types of particles which are repelled by an optical tweezer. To minimize its energy such a particle will move to the area where the electric field is the lowest, namely the zero electric field area at the focal point of an appropriately shaped laser beam.

The optical vortex provides an area of zero electric field much like the hole in a doughnut (toroid). The optical gradient is radial with the highest electric field at the circumference of the doughnut. The optical vortex detains a small particle within the hole of the doughnut. The detention is accomplished by slipping the vortex over the small particle along the line of zero electric field.

The optical bottle differs from an optical vortex in that it has a zero electric field only at the focus and a non-zero electric field at an end of the vortex. An optical bottle may be useful in trapping atoms and nanoclusters which may be too small or too absorptive to trap with an optical vortex or optical tweezers *J. Arlt and M.J. Padgett.* "Generation of a beam with a dark focus surrounded by areas of higher intensity: The optical bottle beam," Opt. Lett. 25, 191-193, 2000.

The optical rotator provides a pattern of spiral arms which trap objects. Changing the pattern causes the trapped objects to rotate. *L. Paterson, M.P. MacDonald, J. Arlt, W. Sibbett, P.E. Bryant, and K. Dholakia*, "Controlled rotation of optically trapped microscopic particles," Science 292, 912-914, 2001. This class of tool may be useful for manipulating non-spherical particles and driving MEMs devices or nano-machinery.

The light cage, (*Neal* in U.S. Patent No. 5,939,716) is loosely, a macroscopic cousin of the optical vortex. A light cage forms a time-averaged ring of optical tweezers to surround a particle too large or reflective to be trapped with dielectric constants lower than the surrounding medium. If the optical vortex is like a doughnut, the light cage is like a jelly-filled doughnut. While the doughnut hole (for the vortex) is an area of zero electric field, the jelly-fill is an area of lowered electric field. In a gross sense, the gradient forces of the plurality of optical tweezers forming the doughnut "push" a particle, with a dielectric constant lower than the surrounding medium, towards the jelly-fill which may also be thought of as the less bright area which lies between the plurality of optical tweezers. However, unlike a *vortex*, no-zero electric field area is created. An optical vortex, although similar in use to an optical tweezer, operates on an opposite principle.

Using a single beam of laser light with a diffractive optical element to form a plurality of diffracted laser beams focused to form an array of optical traps is known in the art. U.S. Patent No. 6,055,106 issued to *Grier and Dufresne* describes arrays of optical traps. The *Grier and Dufresne* patent teaches the use of a dynamic optical element and a focusing lens to diffract the input light beam and generate an array of movable optical traps. The array of optical traps is formed from a single input beam by having an appropriate shape at the back aperture beam diameter. Specifically, that a gaussian TEM_{00} input laser beam should have a beam diameter which substantially coincides with the diameter of the back aperture.

One limitation of having the beam diameter of a gaussian TEM_{00} input laser beam substantially coincides with the diameter of the back aperture is that as shown from a cross sectional view (FIG. 1) a gaussian TEM_{00} beam has much less intensity at its periphery The resulting optical traps will have a similar cross section of intensity.

Accordingly, there has existed a need to have an input beam fill the back aperture and produce optical traps with greater intensity at the periphery. The present invention satisfies these and other needs, and provides further related advantages.

SUMMARY OF THE INVENTION

The present invention provides a novel method and system to use gradient forces to generate and control an array of optical traps.

The present invention provides a novel and improved method, system and apparatus for generating, monitoring and controlling an array of optical traps. The optical traps separately, or in concert, can manipulate small particles.

The present invention employs a first phase patterning optical element, to shape the phase profile of the an input beam of light or energy upstream from a second phase patterning optical element which in turn diffracts the input beam into a plurality of beams.

By patterning the phase of the input beam with the upstream phase patterning optical element the patterned input beam's cross section can be selected to have a substantially even intensity (FIG. 2) even near its periphery. The substantially even intensity of the patterned input beam can be transferred to each beamlet. Accordingly, the plurality of beams produced from the second phase patterning optical element can both have a beam width which coincides with the back aperture of a focusing lens and generate optical traps with greater intensity at the periphery of the optical traps than those optical traps produced from unpatterened input beams which have less intensity at there periphery.

To alter the position of a given optical trap, the beam forming that trap may be steered to a new position with only the second phase patterning optical element, thereby altering the position of the optical trap resulting therefrom.

In other embodiments the first and second phase patterning optical elements may work together to alter the position of a given optical trap, by steering the beam forming that trap and thereby altering the position of that optical trap.

The selective generation and control of the array of optical may be useful in a variety of commercial applications, such as, optical circuit design and manufacturing, nanocomposite material construction, fabrication of electronic components, opto-electronics, chemical and biological sensor arrays, assembly of holographic data storage matrices, rotational motor, mesoscale or nanoscale pumping, energy source or optical motor to drive MEMS, facilitation of combinatorial chemistry, promotion of colloidal self-assembly, manipulation of biological materials, interrogating biological material, concentrating selected biological material, investigating the nature of biological material, and examining biological material.

The activity of the optical trap array, may be observed via an optical data stream (FIG. 5) by placing a beam splitter in the optical pathway. Viewing can be enhanced by introducing a filter to limit the passage of un-diffracted, scattered or reflected light along the pathway of the optical data stream thus reducing this noise which can disrupt video or other monitoring of the optical data stream.

Other features and advantages of the present invention will be set forth, in part, in the descriptions which follow and the accompanying drawings, wherein the preferred embodiments of the present invention are described and shown, and in part will become apparent to those skilled in the art upon examination of the following detailed description taken in conjunction with the accompanying drawings, or may be learned by practice of the present invention. The advantages of the present invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appendent claims.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a chart of the intensity of an unmodified gaussian beam's cross section.

FIG. 2 is a chart of the intensity of a modified gaussian beam with a square cross section

FIG. 3 illustrates a preferred embodiment of a system for generating optical traps to manipulate small particles.

FIG. 4 illustrates a dual transmissive embodiment of a system for generating optical traps to manipulate small particles.

FIG. 5 illustrates an embodiment of a system for generating optical traps to manipulate small particles with transfer lenses.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Certain terminology will be used in the following specification, for convenience and reference and not as a limitation, brief definitions are provided below:

A. *"Beamlet"* refers to a sub-beam of focused light or other source of energy that is generated by directing a focused beam of light or other source of energy, such as that produced by a laser or collimated output from a light emitting diode, through a media which diffracts it into two or more sub-beams. An example of a beamlet would be a higher order laser beam diffracted off of a grating.

B. *"Phase profile"* refers to the phase of light or other source of energy in a cross-section of a beam.

C. *"Phase patterning"* refers to imparting a patterned phase shift to a focused beam of light, other source of energy or beamlet which alters its phase profile, including, but not limited to, phase modulation, mode forming, splitting, converging, diverging, shaping and otherwise steering a focused beam of light, other source of energy or a beamlet.

A preferred embodiment of the inventive apparatus for forming a plurality of movable optical traps, generally designated as 10, is shown in FIG. 1. A movable array of optical traps is formed by generating a focused beam of energy, such as electromagnetic wave energy. In the preferred embodiments, the electromagnetic waves are light waves, preferably having a wavelength of from about 400 nm to about 1060 nm, and more preferably having a wavelength in the green spectrum. The beam is formed of a collimated light, such as the collimated guassian beam output from a laser beam 12, as shown in FIG. 1.

The laser beam 12 is directed through area "A" of a first phase patterning optical element 13, situated upstream from the second phase patterning optical element 14, in a plane conjugate 15 to the planar surface 17 at the back aperture 18 of a focusing lens 20. The preferred embodiment of the focusing lens 20 is an objective lens. The phase profile of the laser beam 12 is patterned by the first phase patterning optical element 14 to form a modified laser beam 22 which is directed at the second phase patterning optical element 14. The second phase patterning optical element 14 has a reflective variable surface medium 24 which the modified laser beam 22 passes through at area "B" which is disposed substantially opposite the planar surface 17 at the back aperture 18.

Beamlets 26 and 28 are formed as the modified laser beam 22 passes through the second phase patterning optical element 14. Each beamlet's 26 and 28 phase profile is selected as the beamlets 26 & 28 are formed. The beamlets then pass through area "C" at the back aperture 18 and are then converged by the focusing lens 20 to form a the optical traps 1000 and 1002 in working focal area 2000 of a vessel 2001. The vessel 2001 constructed of a substantially transparent material, which allows the beamlets to pass through and which does not interfere with the formation of the optical traps.

The second phase patterning optical element may also work in cooperation with the focuing lens 20 to converge the beamlets. The beam diameter w of the beamlets is substantially coincide with the diameter of the back aperture 18. Altering the variable surface medium 24 of the second phase patterning optical element selectively patterns the phase profile of each beamlet.

The working focal area 2000 is that area where a media containing particles or other material to be examined, measured or manipulated by the optical traps 1000 and 1002 is located.

For clarity, only two optical traps 1000 and 1002 are shown, but it should be understood that an array of such optical traps can created by the second phase patterning optical element 14.

Any suitable laser can be used as the source of the laser beam 12. Useful lasers include solid state lasers, diode pumped lasers, gas lasers, dye lasers, alexanderite lasers, free electron lasers, VCSEL lasers, diode lasers, Ti- Sapphire lasers, doped YAG lasers, doped YLF lasers, diode pumped YAG lasers, and flash lamp-pumped YAG lasers. Diode-pumped Nd:YAG lasers operating between 10 mW and 5 W are preferred.

The upstream or first phase patterning optical element is used to at least impart a square cross section (FIG. 2)to the wavefront of the laser beam 12 resulting in a modified laser beam 22 with a square cross section of substantially even intensity. Accordingly, when the beam diameter w of the modified laser beam substantially coincides with the diameter of the back aperture 18 the periphery of the modified laser beam 22 has greater intensity then the periphery of the input beam 12 and the corresponding optical traps 1000 and 1002 will have a corresponding intensity at their periphery. The first phase patterning optical element may also impart different selected wavefronts depending on the parameter of the system, which may include a wavefront which is most intense at the periphery.

In the embodiments shown in FIGS. 3-6 the type, number orientation and position of each optical trap 1000 & 1002 can be selectively controlled by the hologram encoded on the variable surface medium 24 of the second phase patterning optical element 14 which is used to pattern the phase profile of each beamlet. It is a significant feature of the invention that movement of each trap, be it rotation in a fixed position, rotation in a non-fixed position, two-dimensional and three dimensional, continuous and stepped is selectively controllable. The control in this embodiment is achieved by at least varying the hologram formed in the surface medium 24 of the second phase patterning optical element 14.

Moreover, depending on the type of optical trap desired, the phase patterned by the second phase patterning optical element 16 may include wavefront shaping, phase shifting, steering, diverging and converging to form different classes of optical traps including optical tweezers, optical vortices, optical bottles, optical rotators, light cages, and combinations of the different classes

Suitable phase patterning optical elements are characterized as transmissive or reflective depending on how they direct the focused beam of light. Transmissive phase patterning optical elements, as shown in FIGS. 3, 4 and 5, allow the laser beam 12, or in the case of FIG. 4 the laser beam 12 and modified laser beam 22, to pass through. Reflective phase patterning optical elements, as shown in FIGS. 3 and 5, reflect the modified laser beam 22. The upstream, first, phase patterning optical element although shown as a transmissive element in the figures may instead be reflective without departing from the scope of the invention.

Within the two general groups, a phase patterning optical element can be formed from either static or dynamic media. Examples of suitable static phase patterning optical elements include diffractive optical elements with a fixed surface, such as gratings, including diffraction gratings, reflective gratings, transmissive gratings, holograms, stencils, light shaping holographic filters, polychromatic holograms, lenses, mirrors, prisms, waveplates and the like.

The static phase patterning optical element may have different areas, each area configured to impart a different phase profile to the beamlets. In such embodiments, the surface of the static phase patterning optical element can be varied by moving the surface relative to the laser beam to select the appropriate area to change the desired characteristics imparted to the beamlets, i.e., to change the desired phase profile of at least one of the resulting beamlets.

Examples of suitable dynamic phase patterning optical elements having a time dependent aspect to their function include variable computer generated diffractive patterns, variable phase shifting materials, variable liquid crystal phase shifting arrays, micro-mirror arrays, piston mode micro-mirror arrays, spatial light modulators, electro-optic deflectors, accousto-optic modulators, deformable mirrors, reflective MEMS arrays and the like. With a dynamic phase patterning optical element, the features of the surface can be encoded, as previously noted to form a hologram and altered, for example, by a computer, to effect a change in the hologram which can affect the number of beamlets, the phase profile of at least one of the beamlets, and the location of at least one of the beamlets.

Preferred dynamic phase patterning optical elements include phase-only spatial light modulators such as the "PAL-SLM series X7665, manufactured by Hamamatsu of Japan, or "SLM 512SA7" and "SLM 512SA15" both manufactured by Boulder Nonlinear Systems of Lafayette Colorado. These encodeable phase pattern optical elements are computer controllable and multifunctional, so that they can generate the beamlets 26 and 28 by diffracting the modified laser beam 15 and selectively impart desired phase profile (characteristic) to the resulting beamlets.

Turning to the embodiment shown in FIG. 4, the controllable optical traps 42 and 44 are formed by passing the laser beam 12 through area "A" of the first phase patterning optical element 13 which is disposed substantially in a plane 46 opposite the planar surface 17 at the back aperture 18 through which the phase profile of the laser beam 12 is patterned to form a modified laser beam 22 which is directed at a second phase patterning optical element 48.

The second phase patterning optical element 48 has a transmissive variable surface medium 50 which the modified laser beam 22 passes through at area "B" which is disposed substantially opposite the planar surface 17 at the back aperture 18. Beamlets 52 and 54 are formed as the modified laser beam 22 passes through the second phase patterning optical element 48. Each beamlet's 52 and 54 phase profile is selected as the beamlets are formed. The beamlets then pass through area "C" at the back aperture 18 and are then converged by the focusing lens 20 to form the optical traps 42 and 44 in working focal area 2000. The beam diameter "w" of the modified laser beam 22 substantially coincides with the diameter of the back aperture 18. Altering the variable surface medium 50 of the second phase patterning optical element selectively patterns the phase profile of each beamlet.

For clarity, only two optical traps-42 and 44 are shown, but it should be understood that an array of such optical traps can created by the second phase patterning optical element 48.

The embodiment shown in FIG. 5, using additional transfer optics, in some cases can minimize beamlet misalignments. Transfer optics may be particularly useful when the beamlets 62 and 64 are generated off a reflective second phase patterning optical element, or when a data stream to allow behind the focusing lens observation of the activity of the optical traps 66 and 68 is desirous.

A conventional telescope system 70 is disposed between the second phase patterning optical element 14 and a beam splitter 72. The beam splitter 72 is constructed of a dichroic mirror, photonic band gap mirror, omni directional mirror, or other similar device. The beam splitter 72 selectively reflects the wavelength of light used to form the optical traps (beamlets 62 and 64) and transmits other wavelengths such as the imaging illumination 74 provided by an illumination source 76 above the focusing lens 20. The portion of light reflected from the beam splitter 72, which is used to form the optical traps, is then passed through an area "C" of the back aperture 18 of the focusing lens 20.

The imaging illumination 74 passes through the working area 200, along the optical axis of the focusing lens, forming an optical data stream 78 corresponding to the phase profile and location of one or more of the beamlets, derived from the location and position of a small particle contained by an optical trap.

An optical filter element 80, such as a polarizing element or band pass element, is placed within the pathway of the optical data stream 78 to reduce the amount of reflected, scattered or undiffracted laser light passing along the axis of the optical data stream. The filter element 80 filters out one or more preselected wavelengths and, in some embodiments, all but a preselected wavelength of the optical data stream 78.

The optical data stream 78 can then be viewed, converted to a video signal, monitored, or analyzed by visual inspection of an operator , spectroscopically , and/or video monitoring. The optical data stream 78 may also be processed by a photodectector to monitor intensity, or any suitable device to convert the optical data stream to a digital data stream adapted for use by a computer.

To trap small particles an operator and/or the computer will adjust the second phase patterning optical element 14 to direct the movement of each optical trap to acquire a selected small particle and trap it. The plurality of optical traps with contained small particles can then be configured and reconfigured. Using the optical data stream, the position and identity of one or more of the trapped small particles can be monitored, via video camera, spectrum, or an optical data stream which provides a computer controlling the selection of probes and generation of optical traps information useful to adjusting the type of small particles contained by the optical traps. The movement can be tracked based on predetermined movement of each optical trap caused by encoding the phase patterning optical element. Additionally a computer may be used to maintain a record of each probe contained in each optical trap.

Other features and advantages of the present invention will be set forth, in part, in the descriptions which follow and the accompanying drawings, wherein the preferred embodiments of the present invention are described and shown, and, in part, will become apparent to those skilled in the art upon examination of the following detailed description taken in conjunction with the accompanying drawings, or may be learned by practice of the present invention. The advantages of the present invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appendant claims.

We claim:

1. An apparatus for trapping small particles by forming optical traps, comprising:

a first phase patterning optical element for receiving a laser beam and to impart a selected cross section to the wavefront of the laser beam;

a second phase patterning optical element downstream from the first phase patterning optical element for receiving a laser beam and forming at least two beamlets; and,

a focusing lens with a front and a back aperture disposed downstream from the second phase patterning optical element; whereby the second phase patterning optical element in cooperation with the focusing lens can separately converge beamlets and establish the gradient conditions to form optical traps capable of manipulating small particles.

2. The apparatus of claim 1 wherein the first phase patterning optical element, is selected from the group consisting of transmissive and reflective.

3. The apparatus of claim 2 wherein the first phase patterning optical element, is selected from the group consisting of static and dynamic.

4. The apparatus of claim 3 wherein the first phase patterning optical element is selected from the group consisting of gratings, diffraction gratings, reflective gratings, transmissive gratings, holograms, stencils, light shaping holographic filters, polychromatic holograms, lenses, mirrors, prisms, and waveplates.

5. The apparatus of claim 3 wherein the first phase patterning optical element is selected from the group consisting of variable computer generated diffractive patterns, variable phase shifting materials, variable liquid crystal phase shifting arrays, micro-mirror arrays, piston mode micro-mirror arrays, spatial light modulators, electro-optic deflectors, accousto-optic modulators, deformable mirrors, and reflective MEMS arrays.

6. The apparatus of claim 1 wherein the first and second phase patterning optical elements are selected from the group consisting of transmissive and reflective.

7. The apparatus of claim 1 wherein the first and second phase patterning optical elements are selected from the group consisting of static and dynamic.

8. he apparatus of claim 7 wherein at least one of the first and second phase patterning optical elements is selected from the group consisting of gratings, diffraction gratings, reflective gratings, transmissive gratings, holograms, stencils, light shaping holographic filters, polychromatic holograms, lenses, mirrors, prisms, and waveplates.

9. he apparatus of claim 7 wherein at least one first phase patterning optical element, is dynamic and selected from the group consisting of variable computer generated diffractive patterns, variable phase shifting materials, variable liquid crystal phase shifting arrays, micro-mirror arrays, piston mode micro-mirror arrays, spatial light modulators, electro-optic deflectors, accousto-optic modulators, deformable mirrors, and reflective MEMS arrays.

10. The apparatus of claim 3 wherein the first phase patterning optical element is a phase-only spatial light modulator.

11. The apparatus of claim 7 wherein at least on of the first and second phase patterning optical element is a phase-only spatial light modulator.

12. The apparatus of claim 1 further comprising a means for generating a laser beam.

13. The apparatus of claim 12 wherein the means for generating the laser beam is selected from the group consisting of solid state lasers, diode pumped lasers, gas lasers, dye lasers, alexanderite lasers, free electron lasers, VCSEL lasers, diode lasers, Ti- Sapphire lasers, doped YAG lasers, doped YLF lasers, diode pumped YAG lasers, and flash lamp-pumped YAG lasers.

14. The apparatus of claim 1 wherein said focusing lens is an objective lens.

15. The apparatus of claim 1 further comprising a beam splitter disposed opposite the back aperture of the focusing lens, whereby beamlets can be directed at the back aperture and

an optical data stream can pass along the optical axis of the focusing lens from front to back aperture.

16. The apparatus of claim 15 further comprising an optical filter selected from the group consisting of polarizing and band pass disposed along the optical axis of the focusing lens and behind the beam splitter.

17. The apparatus of claim 1 further comprising at least one telescope lens system disposed between upstream from the focusing lens and downstream from the second phase patterning optical element

18. The apparatus of claim 15 further comprising at least one telescope lens system disposed upstream from the beam splitter.

19. The apparatus of claim 15 further comprising at least one telescope lens system disposed downstream from the beam splitter.

20 The apparatus of claim 15 further comprising at least one telescope lens system disposed upstream and downstream from the beam splitter.

21. The apparatus of claim 1 wherein the selected cross section is substantially square.

22. The apparatus of claim 1 wherein the selected cross section is intense at its periphery.

23. A system for trapping small particles by forming movable optical traps, comprising:

a phase patterning optical element for receiving a laser beam and to impart a square cross section to the wavefront of the laser beam;

at least one computer;

a dynamic phase patterning optical element with a variable surface encoded, by the computer, with a hologram for receiving a laser beam from the phase patterning optical element; whereby movable beamlets can be formed from a received laser beam; and,

an objective lens with a front and a back aperture disposed downstream from the dynamic phase patterning optical element; whereby the dynamic phase patterning optical element in cooperation with the objective lens can separately converge beamlets and establish the gradient conditions to form optical traps capable of manipulating small particles.

24. The system of claim 23 further comprising a means for generating a laser beam.

25. The system of claim 23 further comprising a beam splitter disposed oposite the back aperture of the objective lens, whereby beamlets can be directed at the back aperture and an optical data stream can pass along the optical axis of the focusing lens from front to back aperture.

26. The system of claim 23 further comprising a means for converting the optical data stream to a digital data stream adapted for use by a computer.

27. The system of claim 23 further comprising at least one telescope lens system disposed upstream from the objective lens.

28. The system of claim 25 further comprising at least one telescope lens system disposed upstream from the beam splitter.

29. The system of claim 25 further comprising at least one telescope lens system disposed downstream from the beam splitter.

30. The system of claim 25 further comprising at least one telescope lens system disposed upstream and downstream from the beam splitter.

31. The system of claim 26 further comprising an Illumination source.

32. The system of claim 23 wherein the selected cross section is substantially square.

33. The system of claim 23 wherein the selected cross section is intense at its periphery.

34. A method for trapping small particles, comprising :

generating a modified laser beam by imparting a square cross section to the wavefront of a laser beam direct at a first phase patterning optical element;

generating at least two beamlets by directing the modified laser beam at a second phase patterning optical element;

generating optical traps with a vessel by directing the laser beam through a focusing lens;

providing at least two small particles; and

containing the small particles in the optical traps.

35. The method of claim 34 wherein the selected cross section is square.

36. The method of claim 35 wherein the selected cross section has the most intensity at its periphery.

37. A method for manipulating small particles with optical traps, comprising:

generating a modified laser beam by imparting a selected cross section to the wavefront of a laser beam direct at a first phase patterning optical element;

generating at least two beamlets by directing the modified laser beam at a second phase patterning optical element;

generating optical traps within a vessel by directing the beamlets through a focusing lens;

providing at least two small particles within the vessel; and

containing at least one small particle within an optical trap.

38. The method of claim 37, further comprising altering the position of at least one optical trap.

39. The method of claim 37, wherein the optical traps are formed of two or more of optical tweezers, optical vortices, optical bottles, optical rotators, or light cages.

40. The method of claim 37 wherein the selected cross section is square.

41. The method of claim 37 wherein the selected cross section has the most intensity at its periphery.

42. The method of claim 37, wherein each optical trap is independently movable.

43. The method of claim 37, wherein the movement of each optical trap is controlled by a computer.

44. The method of claim 37, wherein the movement of each optical trap is controlled by a computer.

45. A method for manipulating small particles with optical traps, comprising:

generating a modified laser beam by imparting a selected cross section to the wavefront of a laser beam direct at a first phase patterning optical element;

generating at least two beamlets by directing the modified laser beam at a second phase patterning optical element;

providing an optical data stream;

generating optical traps within a vessel by directing the beamlets through a focusing lens;

providing at least two small particles within the vessel; and

containing at least one small particle within an optical trap.

46. The method of claim 45 wherein the movement of each optical trap is controlled by a computer.

47. The method of claim 45, further comprising receiving the optical data-stream with a computer.

48. The method of claim 45, further comprising analyzing the optical data stream with the computer.

49. The method of claim 46, wherein the computer directs the movement of at least one optical trap based on the analysis of the optical data stream.

50. The method of claim 45, further comprising converting the optical data-stream to a video signal.

51. The method of claim 50, further comprising receiving the video signal with a computer.

52. The method of claim 51, further comprising analyzing the video signal with the computer.

53. The method of claim 51, further comprising using the computer to direct the movement of one or more optical traps based on the analysis of the video signal.

54. The method of claim 50, wherein the video signal is used to produce an image.

55. The method of claim 54, further comprising an operator viewing the image and directing the movement of one or more optical traps based on the viewing of the image.

56. The method of claim 45, wherein the optical data stream is spectroscopic data.

57. The method of claim 56, further comprising using a computer to direct the movement of one or more optical traps based on an analysis of the spectroscopic data.

58. The method of claim 45, wherein the optical traps are formed of two or more of optical tweezers, optical vortices, optical bottles, optical rotators, or light cages.

59. The system of claim 45 wherein the selected cross section is intense at its periphery.

60. The method of claim 36 wherein the selected cross section has the most intensity at its periphery.

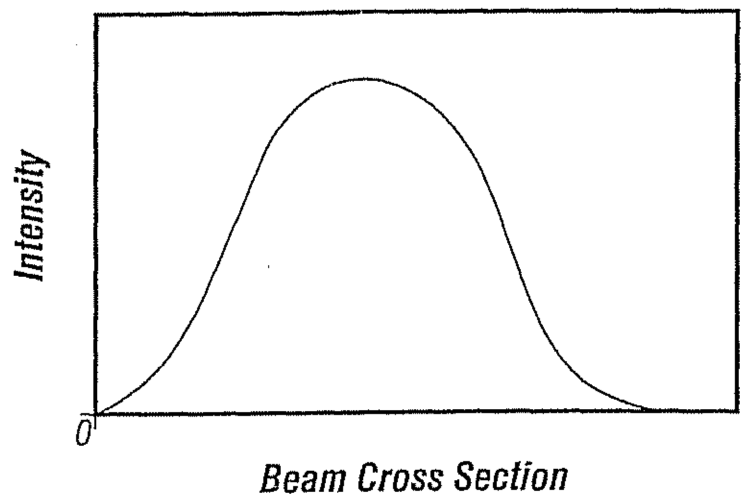
Intensity
0
Beam Cross Section

FIG. 1

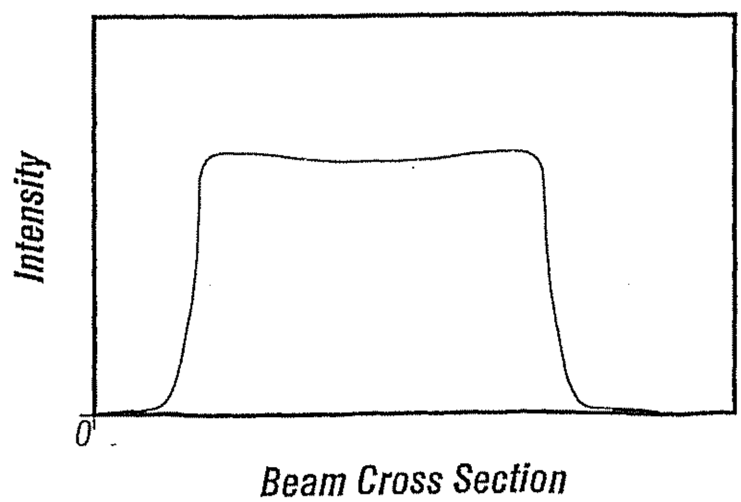
Intensity
0
Beam Cross Section

FIG. 2

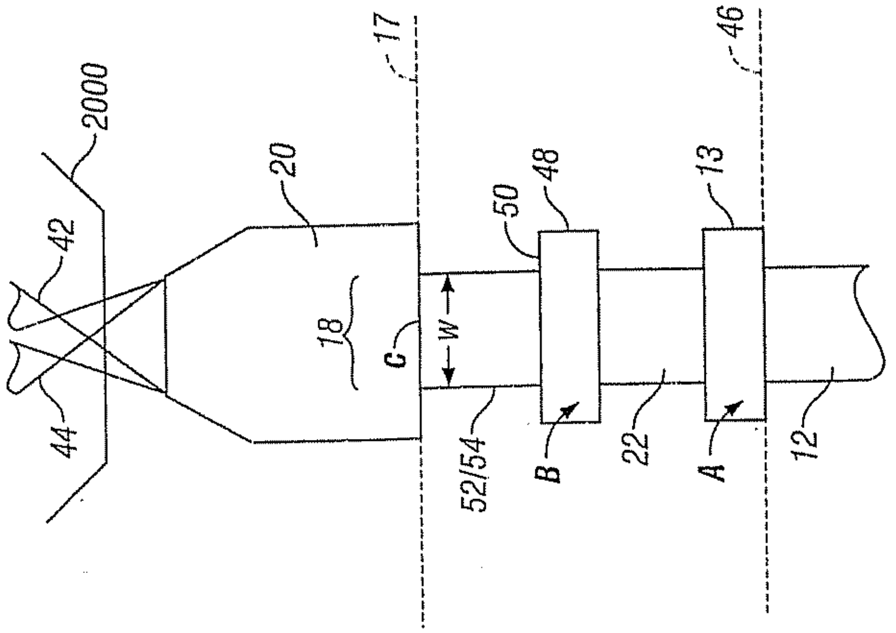
2000
42
44
20
17
18
C
W
50
48
52/54
B
22
13
46
A
12

FIG. 4

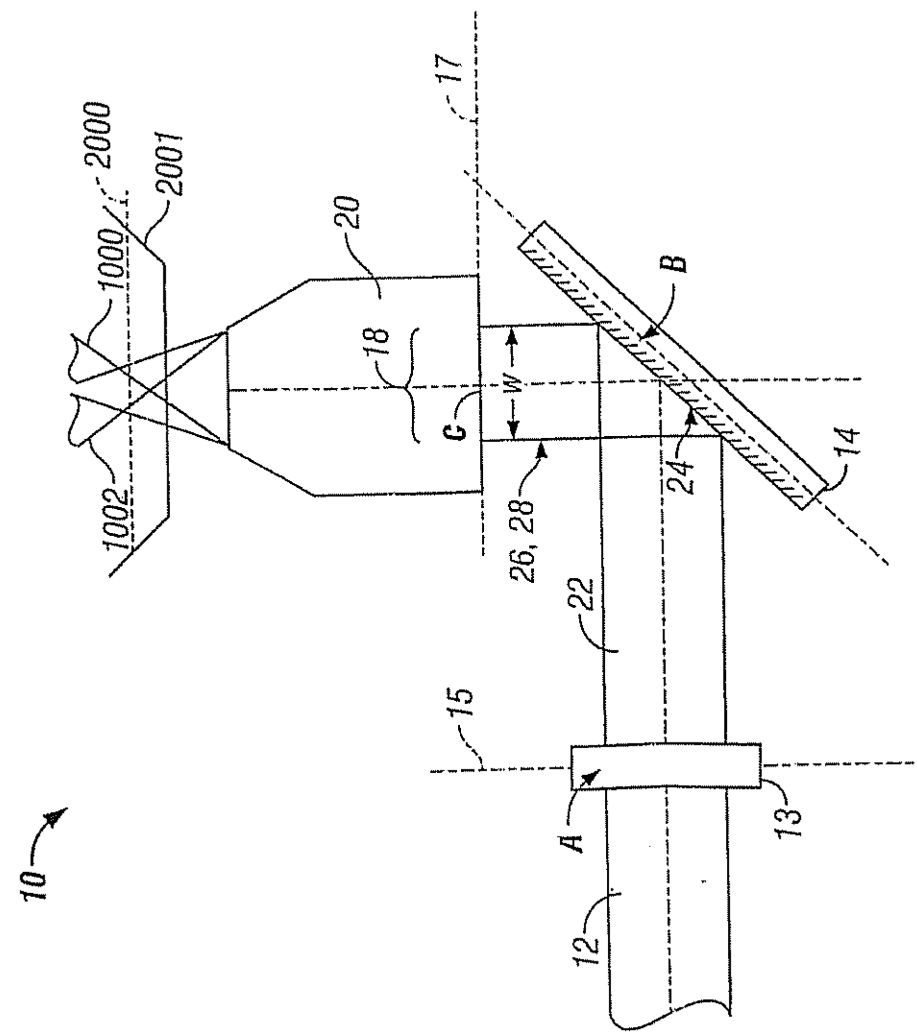
1000
2000
2001
1002
20
17
18
C
W
B
24
14
26, 28
22
15
A
13
12
10

FIG. 3

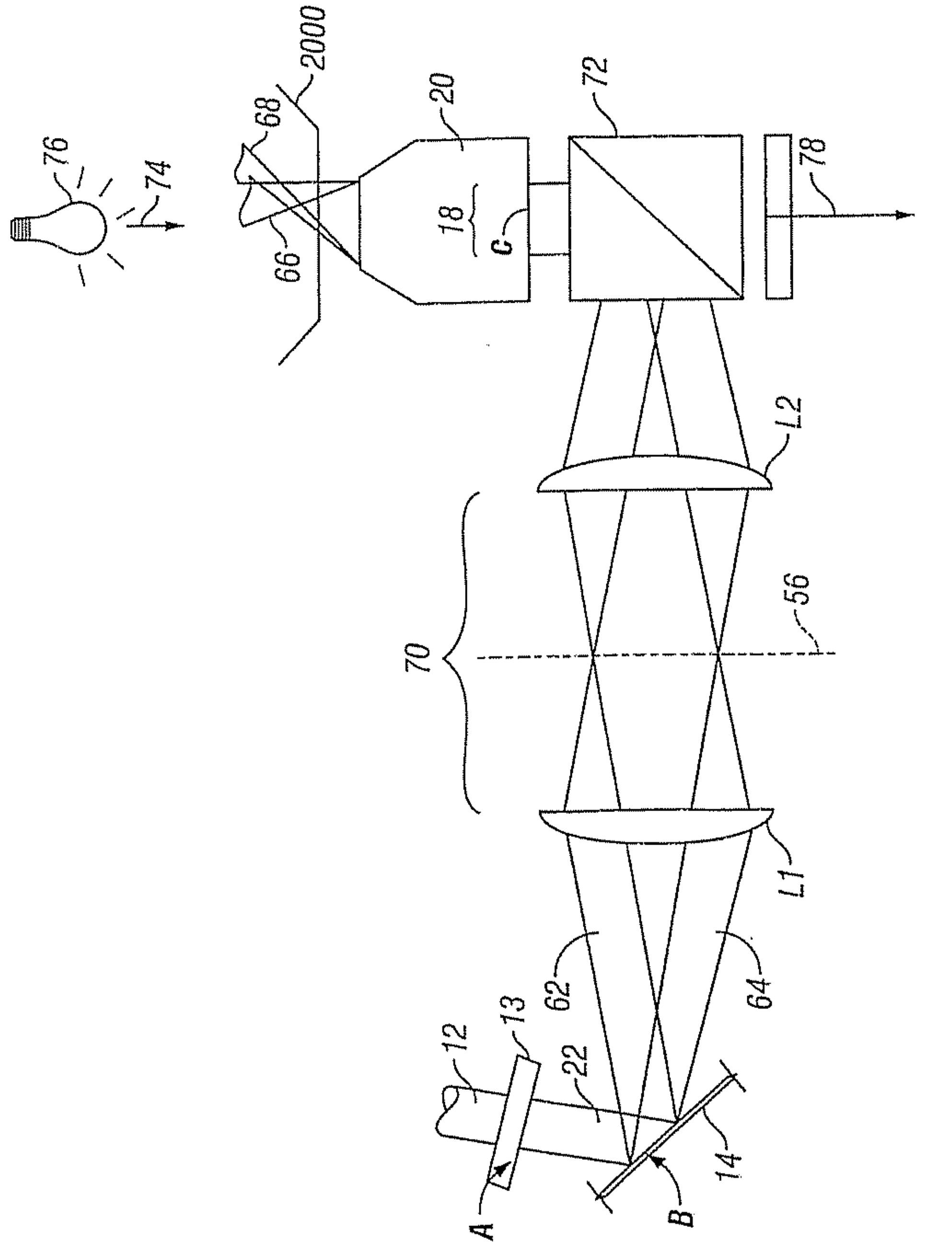

FIG. 5

INTERNATIONAL SEARCH REPORT	International application No. PCT/US03/10936

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H05H 3/04
US CL : 250/251, 359/350,264/482,
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U S : 250/251; 359/350; 264/482

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Mogensen et al Optics Communications. 175,75-81. 15 February 2000

Electronic data base consulted during the international search (name of data base and. where practicable. search terms used)
EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 5.939,716 A (Neal) 17 August 1999 (17 08 1999). see entire document	1-2 ,6,12,14,23-24,34,37,45 ---------- 3-5,7-11,13,15-22,25-33,35-36,38-44,46-60
Y --- A	Mogensen et al , « Dynamic Array Generation and Pattern Formation for Optical Tweezers,Optics Communications», 15 February 2000, Vol. 175, pages 75-81, see entire document	1-2,6,12,14,23-24,34,37,45 ---------- 3-5,7-11,13,15-22,25-33.35-36,38-44,46-60

☐ Further documents are listed in the continuation of Box C ☐ See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure use exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents. such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
04 June 2003 (04.06.2003)	26 SEP 2003
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P O Box 1450 Alexandria Virginia 22313-1450 Facsimile No. (703)305-3230	Authorized officer JOHN R LEE Diane Smith for Telephone No 703-308-0956

Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US03/10936

Box I Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos :
because they relate to subject matter not required to be searched by this Authority, namely:

2 ☐ Claim Nos :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3 ☐ Claim Nos :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box II Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1 ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims

2 ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee

3 ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos :

4 ☐ No required additional search fees were timely paid by the applicant Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos :

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees

[19] 中华人民共和国国家知识产权局

[51] Int. Cl⁷
H05H 3/04

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[43] 公开日 2005 年 8 月 24 日

[11] 公开号 CN 1659935A

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[86] 国际申请 PCT/US2003/010936 2003.4.10
[87] 国际公布 WO2003/088723 英 2003.10.23
[85] 进入国家阶段日期 2004.12.9

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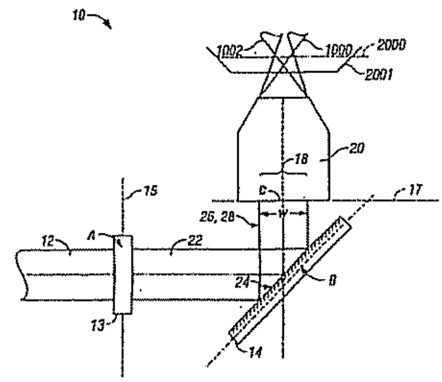
代理人 王永建

权利要求书 7 页 说明书 10 页 附图 3 页

[54] 发明名称 产生和控制光学阱以操纵小微粒的装置和方法

[57] 摘要

本发明总体上涉及用于产生和控制光学阱(1000，1002)以操纵小微粒的装置和方法。输入激光束(12，22)的上游修正提供出具有方形或其它预选强度横截面的射束，其可被用于形成具有对应强度横截面的光学阱(1000，1002)。



ISSN1008-4274

知识产权出版社出版

1．一种通过形成光学阱以捕获小微粒的装置，包括：

一第一相位构图光学元件，以用于接收激光束并将选定的横截面赋予该激光束的波前；

一第二相位构图光学元件，其位于该第一相位构图光学元件的下游，以用于接收激光束并形成至少两个细射束；以及

一聚焦透镜，其具有设置在该第二相位构图光学元件下游的前孔径和后孔径；由此该第二相位构图光学元件协同该聚焦透镜可分别会聚细射束并建立梯度条件，以形成能够操纵小微粒的光学阱。

2．如权利要求1所述的装置，其特征在于，该第一相位构图光学元件选自透射型和反射型相位构图光学元件组成的组。

3．如权利要求2所述的装置，其特征在于，该第一相位构图光学元件选自静态和动态相位构图光学元件组成的组。

4．如权利要求3所述的装置，其特征在于，该第一相位构图光学元件选自光栅、衍射光栅、反射光栅、透射光栅、全息图、模版、光整形全息滤波器、多色全息图、透镜、反射镜、棱镜和波片组成的组。

5．如权利要求3所述的装置，其特征在于，该第一相位构图光学元件选自计算机形成的可变衍射图、可变相移材料、可变液晶相移阵列、微型反射镜阵列、活塞模式微型反射镜阵列、空间光调制器、光电偏转器、声光调制器、变形反射镜和反射MEMS阵列组成的组。

6．如权利要求1所述的装置，其特征在于，该第一和第二相位构图光学元件选自透射型和反射型相位构图光学元件组成的组。

7．如权利要求1所述的装置，其特征在于，该第一和第二相位构图光学元件选自静态和动态相位构图光学元件组成的组。

8．如权利要求 7 所述的装置，其特征在于，第一和第二相位构图光学元件中的至少一个选自光栅、衍射光栅、反射光栅、透射光栅、全息图、模版、光整形全息滤波器、多色全息图、透镜、反射镜、棱镜和波片组成的组。

9．如权利要求 7 所述的装置，其特征在于，第一和第二相位构图光学元件中的至少一个选自计算机形成的可变衍射图、可变相移材料、可变液晶相移阵列、微型反射镜阵列、活塞模式微型反射镜阵列、空间光调制器、光电偏转器、声光调制器、变形反射镜和反射 MEMS 阵列组成的组。

10．如权利要求 3 所述的装置，其特征在于，该第一相位构图光学元件为纯相位空间光调制器。

11．如权利要求 7 所述的装置，其特征在于，该第一和第二相位构图光学元件中的至少一个为纯相位空间光调制器。

12．如权利要求 1 所述的装置，其特征在于，还包括一产生激光束的器件。

13．如权利要求 12 所述的装置，其特征在于，该产生激光束的器件选自固态激光器、二极管泵浦激光器、气体激光器、染料激光器、亚力山大激光器、自由电子激光器、VCSEL 激光器、二极管激光器、钛-兰宝石激光器、掺杂 YAG 激光器、掺杂 YLF 激光器、二极管泵浦 YAG 激光器、闪光灯泵浦 YAG 激光器组成的组。

14．如权利要求 1 所述的装置，其特征在于，所述聚焦透镜为物镜。

15．如权利要求 1 所述的装置，其特征在于，还包括设置在聚焦透镜的后孔径对面的分束器，由此细射束可以在后孔径处被引导，并且光学数据流可以沿聚焦透镜的光轴从前孔径通向后孔径。

16．如权利要求 15 所述的装置，其特征在于，还包括一光学滤光片，

其选自沿聚焦透镜光轴并在分束器后面设置的偏振元件和带通元件组成的组。

17. 如权利要求 1 所述的装置，其特征在于，还包括至少一个设置在聚焦透镜上游和第二相位构图光学元件下游之间的望远镜透镜系统。

18. 如权利要求 15 所述的装置，其特征在于，还包括至少一个设置在分束器上游的望远镜透镜系统。

19. 如权利要求 15 所述的装置，其特征在于，还包括至少一个设置在分束器下游的望远镜透镜系统。

20. 如权利要求 15 所述的装置，其特征在于，还包括至少一个设置在分束器上游和下游的望远镜透镜系统。

21. 如权利要求 1 所述的装置，其特征在于，该选定的横截面基本上为方形。

22. 如权利要求 1 所述的装置，其特征在于，该选定的横截面在外围处具有高强度。

23. 一种通过形成可移动光学阱以捕获小微粒的系统，包括：

一相位构图光学元件，以用于接收激光束从而将一方形横截面赋予激光束的波前；

至少一计算机；

一动态相位构图光学元件，其具有通过计算机用全息图编码的可变表面，以用于接收来自该相位构图光学元件的激光束；由此可由接收到的激光束形成可移动的细射束；以及

一物镜，其具有设置在该动态相位构图光学元件下游的前孔径和后孔径；由此该动态相位构图光学元件协同该物镜可分别会聚细射束并建立梯度条件，以形成能够操纵小微粒的光学阱。

24. 如权利要求 23 所述的系统，其特征在于，还包括产生激光束的

器件。

25．如权利要求23所述的系统，其特征在于，还包括设置在物镜的后孔径对面的分束器，由此细射束可以在后孔径处被引导，并且光学数据流可以沿聚焦透镜的光轴从前孔径通向后孔径。

26．如权利要求23所述的系统，其特征在于，还包括将光学数据流转换成适用于计算机的数字数据流的器件。

27．如权利要求23所述的系统，其特征在于，还包括至少一个设置在物镜上游的望远镜透镜系统。

28．如权利要求25所述的系统，其特征在于，还包括至少一个设置在分束器上游的望远镜透镜系统。

29．如权利要求25所述的系统，其特征在于，还包括至少一个设置在分束器下游的望远镜透镜系统。

30．如权利要求25所述的系统，其特征在于，还包括至少一个设置在分束器上游和下游的望远镜透镜系统。

31．如权利要求26所述的系统，其特征在于，还包括一照明光源。

32．如权利要求23所述的系统，其特征在于，该选定的横截面基本上为方形。

33．如权利要求23所述的系统，其特征在于，该选定的横截面在其外围处具有高强度。

34．一种捕获小微粒的方法，包括：

通过将一方形横截面赋予由第一相位构图光学元件引导的激光束的波前从而产生一修正激光束；

通过由一第二相位构图光学元件引导该修正激光束以产生至少两个细射束；

引导该激光束通过一聚焦透镜，以利用一导管形成光学阱；

提供至少两个小微粒；以及

将该小微粒容纳在该光学阱中。

35．如权利要求34所述的方法，其特征在于，该选定的横截面为方形。

36．如权利要求35所述的方法，其特征在于，该选定的横截面在其外围处具有最强的强度。

37．一种利用光学阱操纵小微粒的方法，包括：

通过将一选定的横截面赋予由第一相位构图光学元件引导的激光束的波前从而产生一修正激光束；

通过由一第二相位构图光学元件引导该修正激光束以产生至少两个细射束；

通过引导该细射束通过一聚焦透镜以在一导管内产生光学阱；

在该导管中提供至少两个小微粒；以及

将至少一个小微粒容纳在一光学阱中。

38．如权利要求37所述的方法，其特征在于，还包括改变至少一个光学阱的位置。

39．如权利要求37所述的方法，其特征在于，该光学阱由两个或多个光学镊子、光学旋涡、光学瓶、光学旋转器或光笼形成。

40．如权利要求37所述的方法，其特征在于，该选定的横截面为方形。

41．如权利要求37所述的方法，其特征在于，该选定的横截面在其外围处具有最强的强度。

42．如权利要求37所述的方法，其特征在于，每个光学阱可独立运动。

43．如权利要求37所述的方法，其特征在于，每个光学阱的运动由

计算机控制。

44．如权利要求 37 所述的方法，其特征在于，每个光学阱的运动由计算机控制。

45．一种利用光学阱操纵小微粒的方法，包括：

通过将一选定的横截面赋予由第一相位构图光学元件引导的激光束的波前从而产生一修正激光束；

通过由一第二相位构图光学元件引导该修正激光束以产生至少两个细射束；

提供一光学数据流；

通过引导该细射束通过一聚焦透镜以在一导管内产生光学阱；

在该导管内提供至少两个小微粒；以及

将至少一个小微粒容纳在一光学阱内。

46．如权利要求 45 所述的方法，其特征在于，每个光学阱的运动由计算机控制。

47．如权利要求 45 所述的方法，其特征在于，还包括用计算机接收该光学数据流。

48．如权利要求 46 所述的方法，其特征在于，还包括用计算机分析该光学数据流。

49．如权利要求 46 所述的方法，其特征在于，计算机基于光学数据流的分析引导至少一个光学阱的运动。

50．如权利要求 45 所述的方法，其特征在于，还包括将该光学数据流转换成视频信号。

51．如权利要求 50 所述的方法，其特征在于，还包括用计算机接收该视频信号。

52．如权利要求 51 所述的方法，其特征在于，还包括用计算机分析

该视频信号。

53．如权利要求 51 所述的方法，其特征在于，还包括基于视频信号的分析，利用该计算机引导一个或多个光学阱的移动。

54．如权利要求 50 所述的方法，其特征在于，该视频信号用于生成一图像。

55．如权利要求 54 所述的方法，其特征在于，还包括操作者基于对图像的观察，观察图像并引导一个或多个光学阱的运动。

56．如权利要求 45 所述的方法，其特征在于，该光学数据流为光谱数据。

57．如权利要求 56 所述的方法，其特征在于，还包括基于光谱数据的分析，利用计算机引导一个或多个光学阱的运动。

58．如权利要求 45 所述的方法，其特征在于，该光学阱由两个或多个光学镊子、光学旋涡、光学瓶、光学旋转器或光笼形成。

59．如权利要求 45 所述的方法，其特征在于，该选定的横截面在其外围处具有高强度。

60．如权利要求 36 所述的方法，其特征在于，该选定的横截面在其外围处具有最强的强度。

产生和控制光学阱以操纵小微粒的装置和方法

背景技术

贯穿本申请参考了不同的出版物。这些出版物的全部内容一并在本申请中作为参考，以便更完整地描述本发明所属技术领域的状况。

1. 技术领域

本发明总体上涉及光学阱。特别是，本发明涉及施加光学梯度力以形成多个光学阱从而操纵小微粒的装置、系统和方法。

2. 相关现有技术的讨论

光学镊子是一种利用聚焦光束的梯度力来操纵绝缘常数高于周围介质的微粒的光学工具。为了使其能量最小化，这种微粒将向电场最高的区域运动。就动量而言，聚焦光束产生辐射压力，由微粒通过光的吸收、反射、衍射或折射产生很小的力。由辐射压力产生的力几乎可以忽略不计，例如以 10mW 功率工作的二极管泵浦 Nd:YAG 激光器的光源只产生几兆分之一牛顿的力。但是，几兆分之一牛顿的力足以操纵小微粒。

可以用于操纵小微粒的其它光学工具包括但不局限于光学旋涡、光学瓶、光学旋转体和光笼。尽管光学旋涡与光学镊子用途类似，但工作原理不同。

光学旋涡在零电场的区域周围产生梯度，这对操纵绝缘常数低于周围介质的微粒、反射型微粒或被光学镊子排斥的其它类型的微粒是有用的。为了使其能量最小化，这种微粒将向电场最低的区域，即在适当形

状激光束的焦点处的零电场区域运动。

光学旋涡提供非常象环形室（电子回旋加速器室）中的孔的零电场区域。光学梯度是放射状的，在环形室的周围具有最高的电场。光学旋涡将小微粒阻止在环形室的孔内。该阻止是通过旋涡在小微粒上沿零电场线滑动来实现的。

光学瓶不同于光学旋涡，它只在焦点处具有零电场，而在旋涡的端部具有非零电场。光学瓶可以用于捕获那些太小或太具有吸收力而不能用光学旋涡或光学镊子捕获的原子和纳米原子团。参见 J. Arlt 和 M. J. Padgett. 在《光学通迅》25, 191-193, 2000 发表的"Generation of a beam with a dark focus surrounded by areas of higher intensity: The optical bottle beam"。

光学旋转器提供捕获目标的空间臂图形。改变图形使捕获的目标旋转。参见 L. Paterson, M. P. MacDonald, J. Arlt, W. Sibbet, P. E. Bryant 和 K. Dholakia 在《科学》292, 912-914, 2001 发表的"Controlled rotation of optically trapped microscopic particles"。这种工具可以用于操纵非球形微粒和驱动 MEMs 器件或纳米机械。

光笼是（Neal 在美国专利 No.5,939,716 中公开的）肉眼可见的光学旋涡类装置。光笼形成光学镊子的平均时间环，以围绕太大或反射性太强而不能用低于周围介质的绝缘常数捕获的微粒。如果说光学旋涡象环形室，光笼就象胶状（jelly-filled）环形室。当环形室的孔（对于旋涡而言）是零电场的区域时，胶状的环形室是较低的电场区。总体而言，形成环形室的多个光学镊子的梯度力朝向也可以认为是位于多个光学镊子之间的较不亮区域的胶状环形室"推动"绝缘常数低于周围介质的微粒。但是，与旋涡不同，它形成非零电场区。尽管光学旋涡与光学镊子用途类似，但工作原理相反。

在本技术领域已知使用具有衍射光学元件的单束激光以形成多个聚焦的衍射激光束来形成光学阱阵列。Grier 和 Dufresne 的美国专利 No. 6,055,106 公开了光学阱阵列。Grier 和 Dufresne 的专利提出使用动态光学元件和聚焦透镜来衍射输入光束并形成可移动的光学阱阵列。在后孔径光束直径处由具有合适形状的单个输入光束形成光学阱阵列。具体地说，高斯 TEM_{00} 输入激光束应具有基本上与后孔径直径一致的光束直径。

高斯 TEM_{00} 输入激光束的光束直径基本上与后孔径直径一致的这一限制从横截面图（图 1）中可以看出，高斯 TEM_{00} 光束在外围处具有更低的强度。得到的光学阱具有类似的强度截面。

因此，有必要使输入光束充满后孔径并在外围处产生具有较高强度的光学阱。本发明可以满足这些以及其它要求，并进一步提供相关的优点。

发明内容

本发明提供一种新颖的方法和系统，以利用梯度力产生和控制光学阱阵列。

本发明提供一种新颖并改进的方法、系统和装置，以用于产生、监视和控制光学阱阵列。该光学阱可以独立或协同操纵小微粒。

本发明采用一第一相位构图光学元件，以修正一第二相位构图光学元件上游的输入光或能量的射束的相位分布，该第二相位构图光学元件反过来将输入射束（分散）衍射成多个射束。

通过用上游的相位构图光学元件形成输入射束的相位图形，即使在其外围附近，也可以将构图输入射束的横截面选择为基本上具有均匀一致的强度（图 2）。基本上均匀强度的构图输入射束可以被传送到每个细射束。因此，由第二相位构图光学元件产生的多个射束可以具有与聚焦

透镜的后孔径一致的射束宽度，并产生多个光学阱，与那些在外围处具有较低强度的由未构图输入光束形成的光学阱相比，该光学阱在外围处具有较高的强度。

为改变给定光学阱的位置，形成光学阱的射束可仅仅通过第二相位构图光学元件操纵到一新的位置，从而改变所得到的光学阱的位置。

在其它实施例中，第一和第二相位构图光学元件可以一起工作，从而通过操纵形成阱的射束并进而改变该光学阱的位置，以改变给定光学阱的位置。

选择性地产生和控制光学阱阵列可以用于各种商业应用，例如光学电路设计和制造、纳米复合材料构造、电子元件的制作、光电子学、化学和生物传感器阵列、全息数据存储矩阵组件、旋转电机、中尺寸或纳米尺寸的泵浦、驱动 MEMS 的能源或光学电机、组合化学的促进、胶状物自组装的改进、生物材料的操纵、生物材料的检查、浓缩选定的生物材料、研究生物材料的性质和测试生物材料。

可以在光路中设置分束器，以通过光学数据流（图 5）观察光学阱阵列的活性。可以加入滤光片以限制非衍射、散射或反射光沿光学数据流的路径通过并减小可能扰乱光学数据流的视频或其它监视效果的噪音，从而加强观察效果。

本发明的其它特征和优点将通过下面的说明书和附图部分阐述，其中，本发明的优选实施例被描述和图示，并部分地通过下面结合附图所做的详细描述对于本领域的技术人员来说是显而易见的或者可以通过本发明的实践而获知。通过后附加权利要求书中提出的手段或工具及其组合可以实现和获得本发明的优点。

附图说明

图 1 是未修正的高斯光束横截面的强度图；

图 2 具有方形横截面的修正高斯光束的强度图；

图 3 示出了用于产生光学阱以操纵小微粒的系统的一优选实施例；

图 4 示出了用于产生光学阱以操纵小微粒的系统的一双重传送实施例；

图 5 示出了带有传递透镜的用于产生光学阱以操纵小微粒的系统的一实施例。

优选实施例的详细描述

为方便和参考而不是作为限制，在下面的说明书中将使用一些术语，它们被简单定义如下：

A．“细射束”（beamlet）指通过引导光或其它能源（例如由激光或从发光二极管的准直输出形成）的聚焦射束经过一将其衍射成两个或多个子束的介质所产生的聚焦光或其它能源的子束。细射束的一个示例是从光栅衍射的高阶激光束。

B．“相位分布”（phase profile）指在射束横截面中的光或其它能源的相位。

C．“相位构图”（phase patterning）指将构图的相移赋予聚焦光、其它能源的射束或改变其相位图的细射束，其包括但不限于相位调制、模式形成、分离、会聚、发散、整形和对聚焦光或其它能源的射束或细射束的其它操纵。

本发明的一优选实施例用于形成多个可移动的光学阱，其在图 1 中总体上以附图标记 10 表示。通过产生一聚焦能量束（例如电磁波能量束）形成一可移动的光学阱阵列。在该优选实施例中，电磁波为光波，其波长优选为从大约 400nm 至大约 1060nm，尤其优选绿色光谱的波长。该光

束形成准直光，例如激光束 12 输出的准直高斯光束，如图 1 所示。

激光束 12 被引导通过第一相位构图光学元件 13 的区域“A”，该第一相位构图光学元件 13 位于一第二相位构图光学元件 14 的上游，并位于与聚焦透镜 20 的后孔径 18 处的平面 17 共轭的平面 15 上。聚焦透镜 20 的优选实施例为一物镜。激光束 12 的相位分布由第一相位构图光学元件 13 构图，以形成修正激光束 22，其被引导至第二相位构图光学元件 14。第二相位构图光学元件 14 具有反射可变表面介质 24，其中修正激光束 22 通过区域“B”，其基本上设置在后孔径 18 的平面 17 的对面。

当修正激光束 22 通过第二相位构图光学元件 14 时，形成细射束 26 和 28。当形成细射束 26 和 28 时，每个细射束 26 和 28 的相位分布被选定。然后，细射束在后孔径 18 处通过区域“C”，接着被聚焦透镜 20 会聚，以在导管 2001 的工作聚焦区 2000 内形成光学阱 1000 和 1002。基本上由透明材料构成的导管 2001 允许细射束通过并不与光学阱的形成干涉。

第二相位构图光学元件也可以协同聚焦透镜 20 来会聚细射束。细射束的射束直径 w 基本上与后孔径 18 的直径相同。改变第二相位构图光学元件的可变表面介质 24 能够可选择地形成各细射束的相位分布图形。

工作聚焦区 2000 是放置包括将要被光学阱 1000 和 1002 检查、测量或操纵的微粒或其它材料的介质的区域。

为简明起见，图中只示出两个光学阱 1000 和 1002，但是，应该理解，可以由第二相位构图光学元件 14 形成这种光学阱的阵列。

可以使用任何适宜的激光器作为激光束 12 的光源。可用的激光器包括固态激光器、二极管泵浦激光器、气体激光器、染料激光器、亚力山大（alexanderite）激光器、自由电子激光器、VCSEL 激光器、二极管激光器、Ti-Sapphire 激光器、掺杂 YAG 激光器、掺杂 YLF 激光器、二极

管泵浦 YAG 激光器、闪光灯泵浦 YAG 激光器。优选在 10mW-5W 之间操作的二极管泵浦 Nd:YAG 激光器。

上游或第一相位构图光学元件用于至少将一方形横截面（图 2）赋予激光束 12 的波前，并导致基本上具有均匀一致的方形强度横截面的修正激光束 22。因此，当修正激光束的光束直径 w 基本上与后孔径 18 的直径一致时，修正激光束 22 的外围强度大于输入光束 12 的外围强度，并且相应光学阱 1000 和 1002 将在它们的外围具有相应强度。第一相位构图光学元件还可以根据系统的参数赋予不同的选定波前，其可包括在外围处最强的波前。

在图 3－5 所示的实施例中，每个光学阱 1000 和 1002 的类型、数量取向和位置可以由在第二相位构图光学元件 14 的可变表面介质 24 上编码的全息图选择性地控制，其中第二相位构图光学元件 14 用于形成各个细射束的相位分布图形。本发明的显著特征在于，选择性地控制各个光学阱的运动，其可以在固定位置转动、在非固定位置转动，可以是二维和三维的、连续和步进的运动。该实施例中的控制通过至少改变在第二相位构图光学元件 14 的表面介质 24 上形成的全息图来实现。

此外，根据需要的光学阱类型，由第二相位构图光学元件 14 形成的相位构图可以包括波前整形、相位移动、转向、发散和会聚，以形成不同种类的光学阱，其中包括光学镊子、光学旋涡、光学瓶、光学旋转器、光笼和不同种类的组合。

适宜的相位构图光学元件为透射型或反射型取决于它们如何引导聚焦光束。如图 3、4 和 5 所示，透射相位构图光学元件允许激光束 12 透过，或在图 4 的情况下，允许激光束 12 和修正激光束 22 透过。如图 3 和 5 所示，反射相位构图光学元件反射修正激光束 22。上游的第一相位构图光学元件虽然图示为透射元件，但其也可以用反射型元件代替，且

不超出本发明的范围。

在两个总组中，相位构图光学元件可以由静态或动态介质形成。适宜的静态相位构图光学元件的示例包括具有固定表面的衍射光学元件，例如光栅，包括衍射型光栅、反射光栅、透射光栅、全息图、模版、光整形全息滤波器、多色全息图、透镜、反射镜、棱镜和波片等。

静态相位构图光学元件可以具有不同的区域，各个区域设置成将不同的相位分布赋予细射束。在这种实施例中，静态相位构图光学元件的表面可以通过相对激光束移动该表面来改变，以选择适宜的区域而改变赋予细射束的所需特征，即改变至少一个得到的细射束的所需相位分布。

功能随时间变化的适宜的动态相位构图光学元件的示例包括：可变的计算机生成的衍射图、可变的相移材料、可变的液晶相移阵列、微型反射镜阵列、活塞型微反射镜阵列、空间光调制器、光电偏转器、声光调制器、可变形反射镜、反射 MEMS 阵列等。用动态相位构图光学元件可以对表面特征进行编码（例如如前所述形成一全息图），或例如借助计算机进行改变，以影响全息图的变化，其可以影响细射束的数量、至少一个细射束的相位图和至少一个细射束的位置。

优选的动态相位构图光学元件包括纯相位空间光调制器，例如由日本 Hamamatsu 制造的“PAL-SLM 系列 X7665”或由 Boulder Nonlinear Systems Colorado Lafayette 制造的“SLM 512SA7”和“SLM 512SA15”。这些可编码相位构图光学元件是可由计算机控制的和多功能的，因此，它们可以通过衍射修正激光束 15 产生细射束 26 和 28，并选择性地将所需的相位分布（特征）赋予所获得的细射束。

回过来参看图 4 所示的实施例，激光束 12 通过第一相位构图光学元件 13 的“A”区域形成可控制光学阱 42 和 44，该第一相位构图光学元件 13 基本上设置在与后孔径 18 处的平面 17 相对的平面 46 上，激光束

12的相位分布通过该第一相位构图光学元件构图，以形成修正激光束22，其被引导至第二相位构图光学元件48。

第二相位构图光学元件48具有透射可变表面介质50，其中修正激光束22透过基本上设置在后孔径18处的平面17的相对位置上的区域“B”。当修正激光束22透过第二相位构图光学元件48时，形成细射束52和54。随着细射束的形成，各细射束52和54的相位分布被选择。然后，细射束透过后孔径18处的区域“C”，接着由聚焦透镜20会聚，并在工作聚焦区2000中形成光学阱42和44。修正激光束22的光束直径“w”基本上与后孔径18的直径一致。改变第二相位构图光学元件的可变表面介质50，从而选择性地形成各细射束的相位分布图形。

为简明起见，图中仅示出两个光学阱42和44，但是，应该理解，可以由第二相位构图光学元件形成这种光学阱的阵列。

图5所示的实施例使用了附加的传递光学元件，其在某些情况下可以最小化细射束的未准直。当通过反射型第二相位构图光学元件形成细射束62和64时，或当需要数据流以允许在聚焦透镜后面观察光学阱66和68的活性时，传递光学元件特别有用。

一传统的望远镜系统70设置在第二相位构图光学元件14和分束器72之间。分束器72由分光镜、光子带隙反射镜、全反射镜或其它类似的器件构成。分束器72选择性地反射用于形成光学阱（细射束62和64）的波长的光并透射其它波长的光，例如由聚焦透镜20上方的照明光源76提供的成像照明光74。然后，用于形成光学阱的从分束器72反射的部分光通过聚焦透镜20的后孔径18的区域“C”。

成像照明光74沿聚焦透镜的光轴通过工作区2000，从而形成对应于由光学阱包含的小微粒的定位和位置衍生的一个或多个细射束的相位分布和位置的光学数据流78。

光学滤光元件 80（例如偏振元件或带通元件）设置在光学数据流 78 的路径内，以减小沿光学数据流的轴线通过的反射、散射或非衍射激光的量。滤光元件 80 滤除一个或多个预选波长，且在某些实施例中，滤除除了光学数据流 78 的预选波长之外的所有波长的光。

然后，光学数据流 78 转换成视频信号，从而可通过操作者的视觉检查、光谱、和／或视频监视观察、监视或分析光学数据流 78。光学数据流 78 还可以用光探测器处理，以监视强度，或用任何适宜的装置将光学数据流转换成适用于计算机使用的数字数据流。

为捕获小微粒，操作者和／或计算机将调整第二相位构图光学元件 14，以引导各个光学阱的运动，从而获得选定的小微粒并捕获它。然后，可以构造和重新构造包含小微粒的多个光学阱。利用该光学数据流，通过摄像机、光谱或光学数据流可以监视一个或多个捕获的小微粒的位置和特性，其向一计算机提供控制探测器的选择和光学阱的产生的信息，以用于调整光学阱包含的小微粒的类型。基于对相位构图元件进行编码造成的各个光学阱的预定运动，可以跟踪该运动。另外，一计算机可以用于保留在各个光学阱中包含的各探测器的记录。

本发明的其它特征和优点将通过下面的说明书和附图部分阐述，其中，本发明的优选实施例被描述和图示，并部分地通过下面结合附图所做的详细描述对于本领域的技术人员来说是显而易见的或者可以通过本发明的实践而获知。通过后附加权利要求书中提出的手段或工具及其组合可以实现和获得本发明的优点。

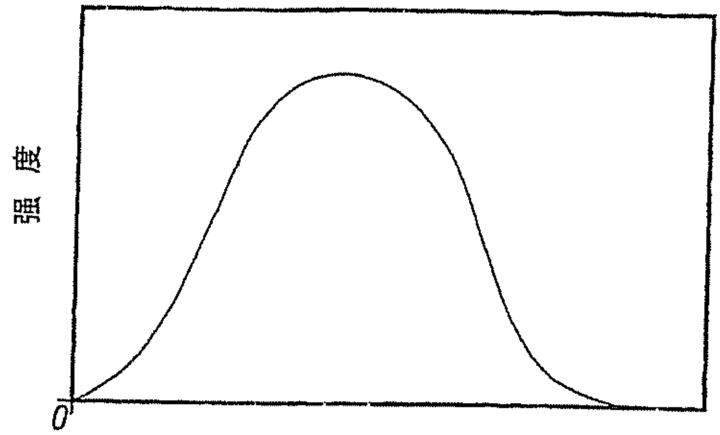


图1

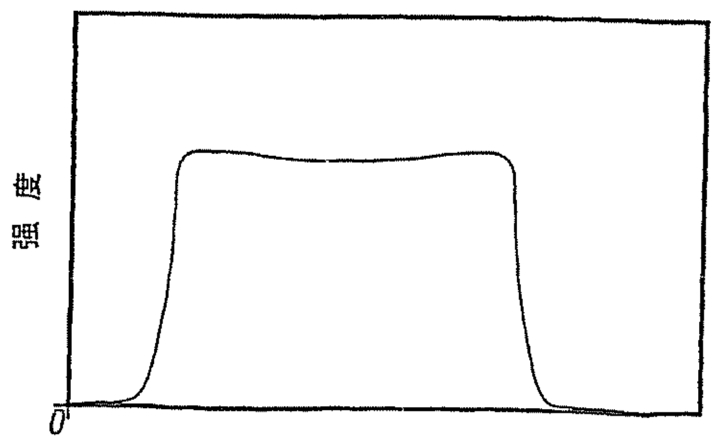


图2

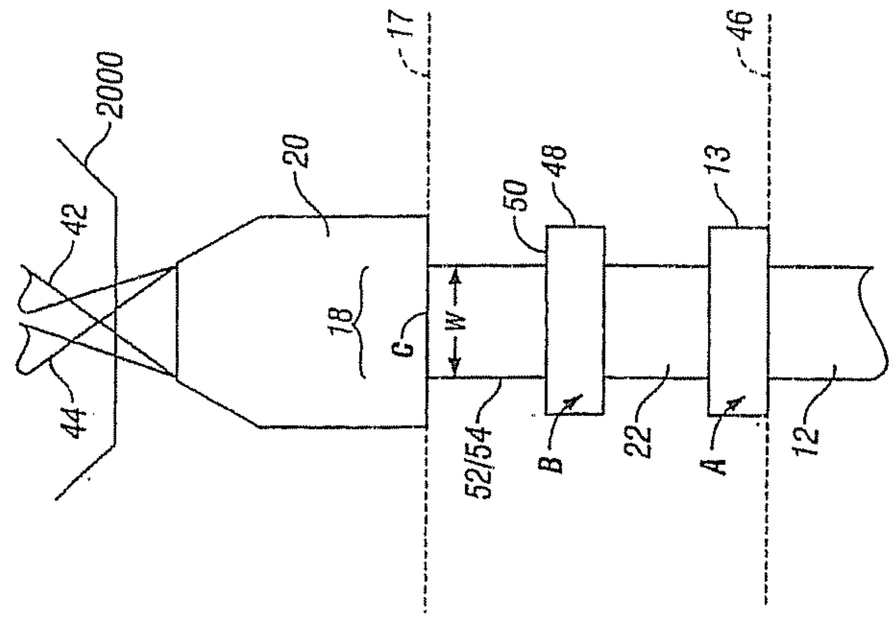

2000
42
44
20
18
C
W
17
46
48
50
13
52/54
B
22
A
12

图4

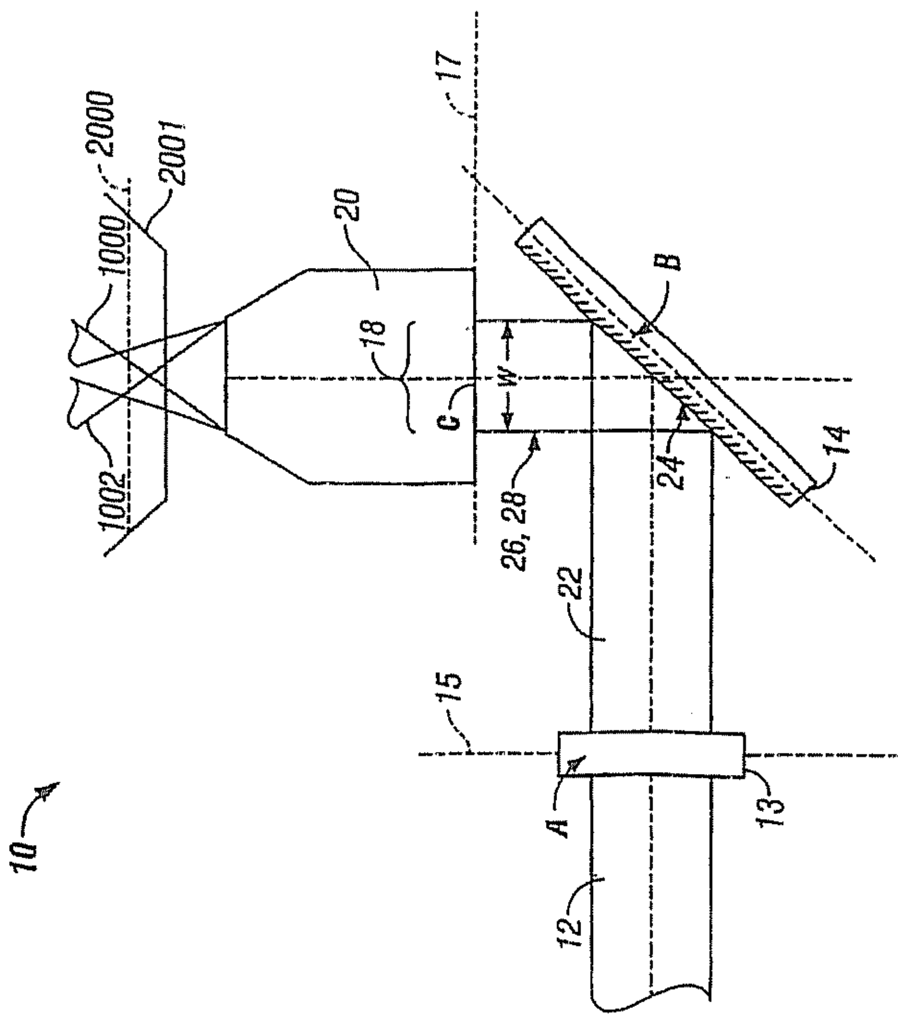

10
2000
2001
1000
1002
20
18
C
W
17
B
24
14
26, 28
22
15
A
13
12

图3

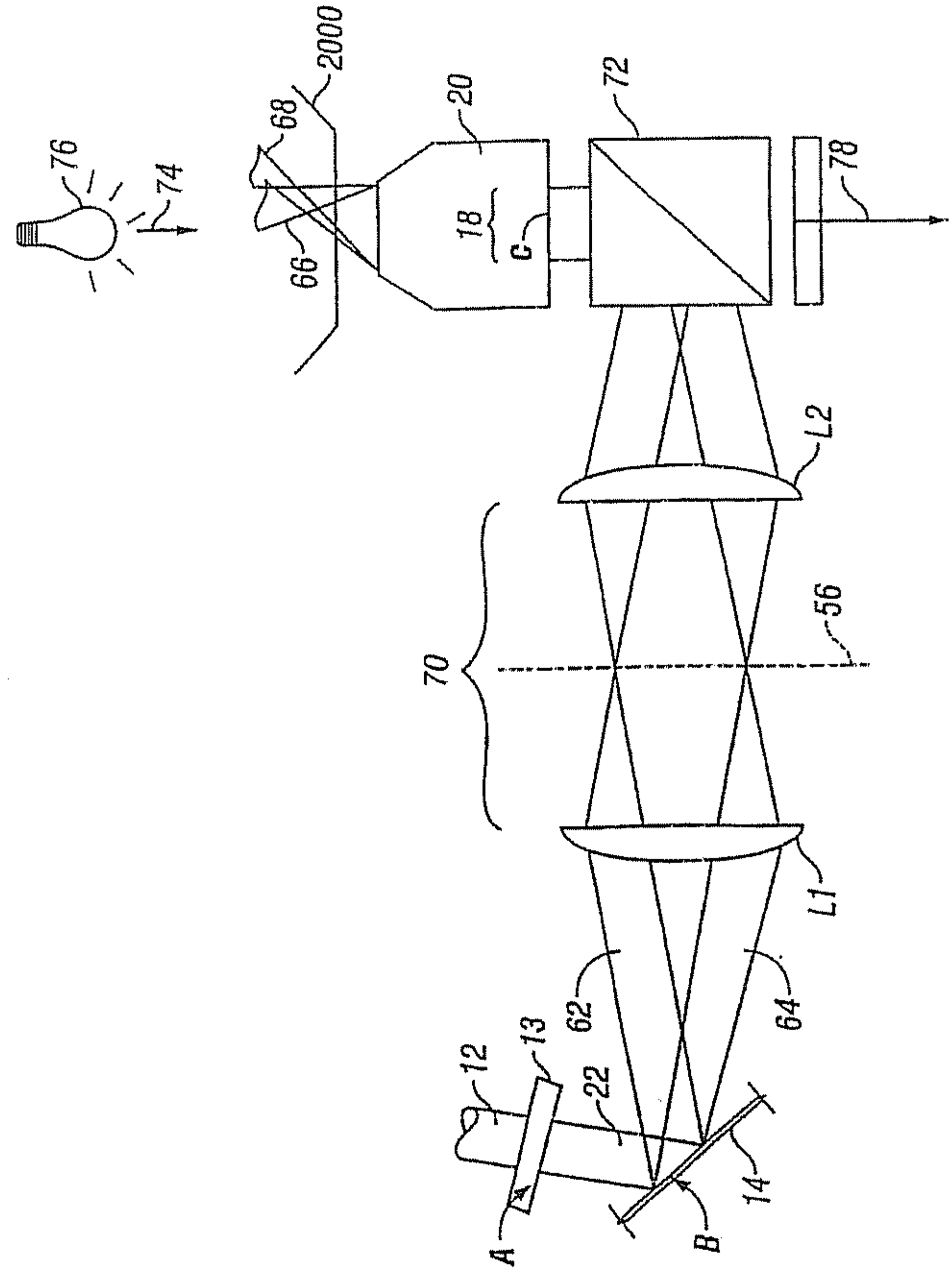


图5